

Suppression of the virtual Anderson transition in a narrow impurity band of doped quantum well structures.

N. V. Agrinskaya,* V. I. Kozub, and D. S. Poloskin

Ioffe Physical-Technical Institute of the Russian Academy of Sciences, 194021, Saint Petersburg, Russia.

Earlier we reported an observation at low temperatures of activation conductivity with small activation energies in strongly doped uncompensated layers of p-GaAs/AlGaAs quantum wells. We attributed it to Anderson delocalization of electronic states in the vicinity of the maximum of the narrow impurity band. A possibility of such delocalization at relatively small impurity concentration is related to the small width of the impurity band characterized by weak disorder. In this case the carriers were activated from the "bandtail" while its presence was related to weak background compensation. Here we study an effect of the extrinsic compensation and of the impurity concentration on this "virtual" Anderson transition. It was shown that an increase of compensation initially does not affect the Anderson transition, however at strong compensations the transition is suppressed due to increase of disorder. In its turn, an increase of the dopant concentration initially leads to a suppression of the transition due an increase of disorder, the latter resulting from a partial overlap of the Hubbard bands. However at larger concentration the conductivity becomes to be metallic due to Mott transition.

I. INTRODUCTION

In our previous papers [1], [2] we reported an observation of delocalized electronic states in the vicinity of the maximum of a narrow impurity band in GaAs/AlGaAs quantum well structures. It is important that such a delocalization took place at dopant concentrations significantly smaller than ones corresponding to the Mott-Anderson criterion. Such a behavior we described as a manifestation of the virtual Anderson transition - because, despite of a presence of delocalized states, transport of the majority carriers over these (occupied) states was blocked by the Hubbard correlations. The smallness of the critical concentration for the Anderson transition was explained by a weakness of the random potential and, correspondingly, by a smallness of the scatter of localized states energies. In this case linear carrier transport was supported by minority carriers activated from acceptors ionized by background impurities. Note that such a behavior can be realized only 2D systems, where the background compensating defects can be situated outside of the 2D layer which is important for a formation of the narrow impurity band. Since the conductivity was related to a presence of finite (but weak) compensation and to activation of the minority carriers situated in the bandtail to the band of delocalized states, the corresponding activation energy was by an order of magnitude smaller than the activation energy of the dopant. Another mechanism of conductivity over the delocalized states was relevant for the case of strong enough electric fields. It was related to an impact ionization of the minority carriers to the band of delocalized states. According to the considerations given above, our picture corresponds to the case when the Fermi level is situated below the mobility edge within the impurity band. One could expect that an increase of a compensation degree, which shifts the Fermi level towards the mobility edge, finally would lead to purely metallic (non-activated) conductivity. However, an increase of the compensation can lead to an increase of disorder, i.e. to an increase of the critical concentration, and, finally, to a suppression of the delocalization.

In its turn, as we noted earlier [1], an increase of the dopant concentration can also lead to a suppression of the virtual Anderson transition. Indeed, an increase of this concentration can lead to an overlap of the two Hubbard bands and to appearance of the charged centers not related to compensation. Again, the additional charge disorder can suppress the delocalization. However the further increase of the dopant concentration finally leads to the Mott transition when the Fermi level reaches the mobility edge of the upper Hubbard band. Thus, it was of interest to study an effect of both compensating centers concentration (introduced artificially) and of the dopant concentration on the manifestation of the virtual Anderson transition. It is this investigation which is reported in this paper. We will show that an increase of compensation initially leads to a decrease of the activation energy in agreement to the considerations given above. The further increase of compensation leads to a complete suppression of the virtual Anderson transition which is accompanied by a significant broadening of the impurity band. The latter manifests itself in an increase of the all activation energies. Then, an increase of the dopant concentration in uncompensated samples

*Electronic address: nina.agrins@mail.ioffe.ru

also initially leads to a suppression of the virtual Anderson transition. However at large enough concentrations the metallic state resulting from the Mott transition is formed.

II. EXPERIMENT

We have studied two sets of $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well samples, grown by molecular epitaxy technique. The samples contained 5 quantum wells with a width 15 nm separated by $Al_{0.3}Ga_{0.7}As$ barriers with a thickness 100 nm. At the first set of samples only quantum wells centers (5 nm) were doped by Be with large enough concentration $(1-3) \cdot 10^{12} \text{ cm}^{-2}$ (samples N 1,2). At the second set of samples the centers of the quantum wells were also doped by Be, however the centers of barriers (5 nm) were doped by compensating impurity (Si), see Table 1 (samples 3,4). Thus, the degrees of compensation $K = N_D/N_A < 0,01$ were less than 0.01 for samples 1,2 and for samples 3 and 4 $K=0.1$ and $K=0.5$, respectively. The acceptor concentration in the wells was taken to be large enough to ensure a presence of delocalized states in the center of impurity band of A_0 centers (resulting from the virtual Anderson transition)[1], [2].

N	N_A, cm^{-2}	N_D, cm^{-2}	p_{300K}, cm^{-2}	$\varepsilon_1 \text{ meV}$	$\varepsilon_4, \text{meV}$	$K = N_D/N_A$
1-7-582	$2,5 \cdot 10^{12}$	-	$2 \cdot 10^{12}$	-	-	≤ 0.01
2-7-580	$1,5 \cdot 10^{12}$,	$1 \cdot 10^{12}$	21	2	≤ 0.01
3-8-291	$1 \cdot 10^{12}$	Si, $1,5 \cdot 10^{11}$	$1 \cdot 10^{12}$	21	2	0.1
4-8-292	$1 \cdot 10^{12}$	Si, $5 \cdot 10^{11}$	$5 \cdot 10^{11}$	40	10	0.5

Table 1. Parameters of the studied samples

On Fig.1(a,b) we give the temperature curves of the conductivity σ and of carrier concentration P (obtained from the Hall coefficient R_h) for all of the samples.

As it was noted in our previous paper [3], one of the features characterizing the virtual Anderson transition in the impurity band is a mixed conductivity (over the allowed and impurity bands) which manifests itself as a presence of a characteristic minimum in temperature behavior of concentration. At higher temperatures there exists a part of the curve corresponding to activation of the carriers from the Fermi level to the allowed band - energy ε_1 (in more detail see about a calculation of this activation energy for the case of the mixed conductivity in [3]). This minimum appears to be deeper with a sharp increase of the effective concentration and, correspondingly, with a decrease of the Hall mobility at temperatures 20-30 K provided the carriers in the allowed band and in the impurity band have opposite charges. When calculating the mixed concentration m from the Hall effect one should take into account that in the impurity band completely filled by holes the carriers can be of the opposite sign, their number being $P_2 = N_D + P_1$. Thus the equation for the Hall concentration P_H is modified in the following way:

$$P_H = \frac{(N_D + P_1 + bP_2)^2}{b^2P_1 - N_D - P_1} \quad (1)$$

where $P_1 = N_V \exp(\varepsilon_F/k_B T)$ is the carrier concentration within the valence band, b is a ratio of mobilities in the allowed and impurity bands, μ_1 and μ_2 .

Note that the r.h.s. of Eq. 1 can diverge (tend to infinity) when the concentrations of electrons in the impurity band and concentration of holes in the valence band are nearly equal. Thus the Hall concentration at some temperatures can appear to be larger, than the concentration at room temperature. The mixed conductivity (in contrast to mixed concentration) has no maxima (at least if one does not take into account temperature behavior of the mobility) and is given as

$$\sigma_m = (P_1b + N_A - N_D - P_1)\mu_1 \quad (2)$$

$$P_H = \frac{(N_D + P_1 + bP_2)^2}{b^2P_1 - N_D - P_1} \quad (3)$$

$$\sigma_m = (P_1b + N_A - N_D - P_1)\mu_1 \quad (4)$$

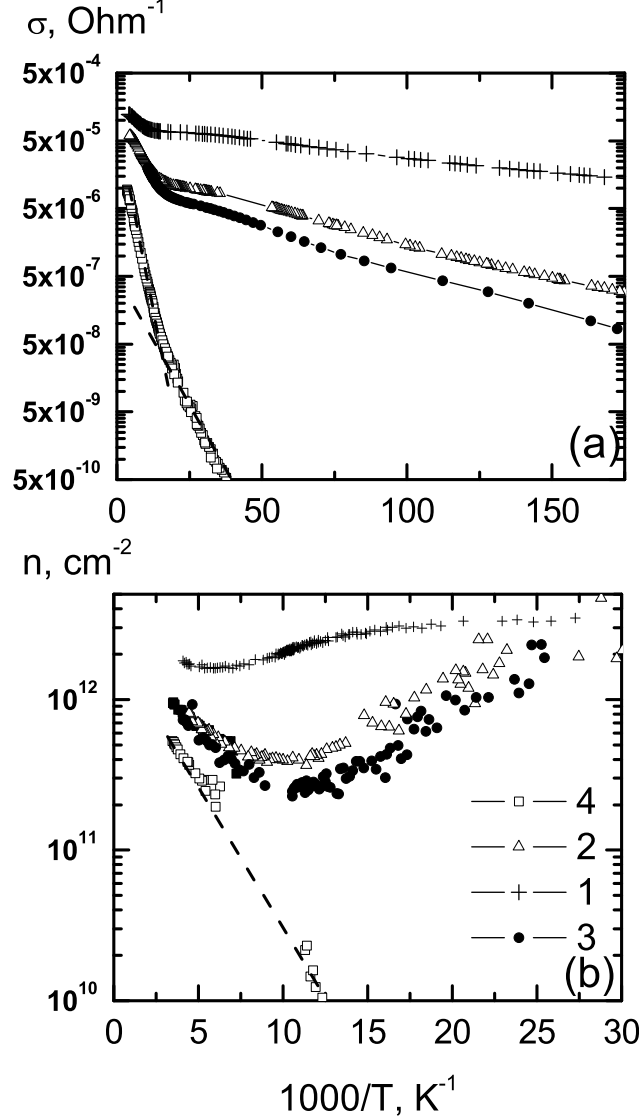


FIG. 1: Temperature dependence of the (a) conductivity and (b) hole concentration for all samples listed in the table.

This region of the mixed conductivity manifests itself as a shoulder in the conductivity temperature curves. At the lower temperatures the temperature behavior is controlled by the activation energy ε_4 (related to an activation of the carriers from the Fermi level to the mobility edge within the impurity band). At the weak compensations this energy is about a halfwidth of the impurity band.

When only centers of the wells are doped, there exists the filled impurity band of the singly occupied acceptors A_0 , where the compensation degree is small enough and is controlled by a presence of random donor impurities in the barrier ($N_D < 10^{16} \text{ cm}^{-3}$). The delocalized states appear in this band at concentration $N_A \sim 10^{18} \text{ cm}^{-3}$. In this case the concentration of carriers within the allowed band a standard expression for weakly compensated impurity can be used. Such a behavior is observed for doped quantum wells without intended compensation or at weak compensation (samples 2 and 3). Temperature behavior of conductivity at small temperatures has an activated character with a small energy ε_4 . At temperatures less than 4 K, these samples demonstrated the breakdown behavior related to the impact ionization of the carriers from the Fermi level to the mobility edge.

An important difference between the weakly compensated sample N2 from the uncompensated N1 is about twice less value of the activation energy ε_4 , as well as the breakdown behavior at higher temperatures (around 4 K), see Fig.2 (note that the measurements were made at constant current 1 nA).

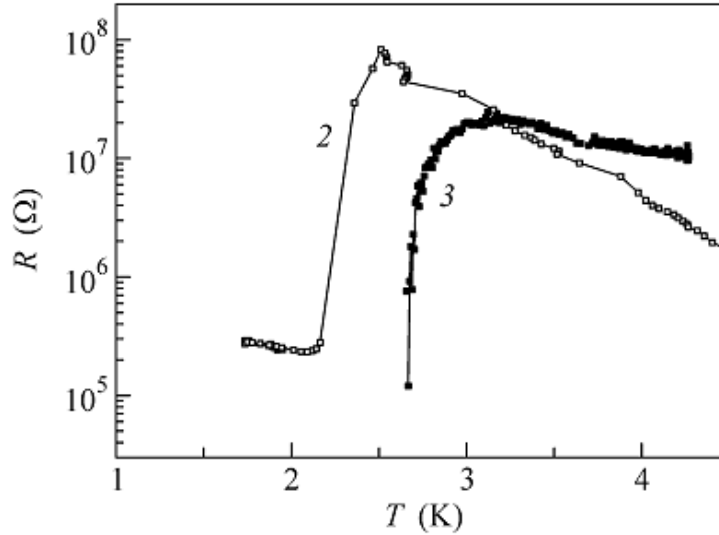


FIG. 2: Temperature dependence of the low-temperature conductivity of samples 2 and 3 measured in the constant current regime at the current of 1 na.

In the sample with a strong compensation degree N4 ($N_D/N_A \sim 0,5$) the mixed conductivity as well as activated temperature behavior at small temperatures and the breakdown behavior were not observed. It is related to the significant increase of disorder and, correspondingly, to the increase of the width of the impurity band which leads to a suppression of the Anderson transition. The activation energy ε_1 (obtained from the Hall data) in this sample is ~ 40 meV which exceeds significantly the corresponding energies for weakly compensated samples. In its turn, the low temperature conductivity behavior demonstrates activation energy $\varepsilon_3 \sim 10$ meV. If one relates this energy to the nearest neighbor hopping, it corresponds to the halfwidth of the impurity band. An increase of the energy ε_1 for the strong compensation limit, according to [4], is equal to $\varepsilon_1 = \varepsilon_0 + \varepsilon_3$, which for $\varepsilon_0 = 30$ meV gives the observed energy $\varepsilon_1 = 40$ meV. The variable range hopping was not observed due to very large values of resistance at low temperatures.

With an increase of the doping level the sample N1 demonstrates weaker temperature dependencies of the conductivity and Hall effect (Fig.1). This sample exhibits effects of weak localization in temperature behavior of conductivity as well as in magnetoresistance (MR) (Fig.3). At low temperatures in weak magnetic fields MR appears to be positive (antilocalization), then a transition to negative MR is observed (weak localization). This behavior correlates to the one of quasimetallic samples (see [5]). Such a behavior evidences the Mott transition (overlapping of the upper and lower Hubbard bands).

III. DISCUSSION

1. Role of compensation.

As it was noted earlier, one could expect that an increase of compensation degree, shifting the Fermi level μ within the impurity band towards the band of delocalized states could finally to nullify the activation energy ε_4 which would mean a transition to metallic state. Indeed, assuming that the density of states of the impurity band has Gaussian shape, for small concentrations of the compensating donors one obtains

$$\int_{-\infty}^{\mu} g_0 \exp\left(-\left(\frac{\varepsilon_0 - \varepsilon'}{\Delta\varepsilon_0}\right)^2\right) d\varepsilon' = N_d \quad (5)$$

where ε_0 corresponds to a center of the impurity band, $\Delta\varepsilon_0$ is the halfwidth of the impurity band at the limit of small N_d . The latter is controlled mostly by deformational effects of non-Coulombic nature and by the order of magnitude coincides with energy ε_4 observed for weakly compensated samples. In this case the shift of the Fermi level is given as

$$\frac{\partial\mu}{\partial n_d} = g_0^{-1} \exp\left(\left(\frac{\varepsilon_0 - \mu}{\Delta\varepsilon_0}\right)^2\right) \quad (6)$$

It is seen that for small N_d when the Fermi level is deep within the tail of the impurity band, an increase of N_d initially leads to strong shift of μ and, correspondingly, to a decrease of ε_4 . However an increase of the Coulomb disorder leads to the broadening of the impurity band which can be estimated as

$$\Delta\varepsilon_C \sim \frac{e^2 N_d^{1/2}}{\kappa} \quad (7)$$

Correspondingly, finally this broadening can exceed the value of $\Delta\varepsilon_0$. According to considerations, given in our papers [1], [2], the criterion for Anderson transition for significantly compensated samples obtains a form

$$N_A a^2 \geq \frac{\alpha}{\ln(\varepsilon_0/(\Delta\varepsilon_C))} \quad (8)$$

where N_A is a concentration of dopant acceptors, a is the localization length while α is of the order of unity.

This equation can be compared with a criterion of Anderson transition in non-compensated samples :

$$N_A a^2 \geq \frac{\alpha}{\ln(\varepsilon_0/(\Delta\varepsilon_0))} \quad (9)$$

Since the mobility edge is expected to be situated in the vicinity of the band center, an increase of the compensation can shift the sample to the metallic state only at small degrees of compensation. When the Fermi level reaches a vicinity of the band center it inevitably means an increase of $\Delta\varepsilon_C$ up to the values significantly exceeding ε_0 . As it is seen from the comparison of the criteria 8 and 10, this leads (for fixed concentration N_A) to a suppression of the virtual Anderson transition.

As it is seen from the estimate 7, at compensating donor concentrations $\sim 10^{-11} \text{ cm}^{-2}$ the magnitude of the disorder potential is of the order of $\sim 6 \text{ meV}$. Thus in the sample 3 with a small degree of compensation with the concentration of the compensating donors given above the energy $\Delta\varepsilon_C$ appears to be comparable to the energy $\Delta\varepsilon_0$ (characterizing the bandwidth without compensation). Indeed, according to our estimates ([1], [2]) the energy $\Delta\varepsilon_0$ is of the order of 6 meV . This estimates is compatible to the activation energy $\varepsilon_4 \sim 2 \text{ meV}$.

This scenario completely agrees with experiment. In particular, for moderate degree of compensation ($K = 0.1$, sample 3) the criterion of the Anderson transition 8 is still met, and the observed picture is similar to the one of the sample 1. Note that despite of the expected shift of the chemical potential towards the center of the band, it does not lead to a significant decrease of the activation energy. This is due to the fact that the effect of the shift of μ is compensated by the effect of the broadening of the very impurity band, as well as by a narrowing of the band of Anderson-delocalized states due to an increase of disorder. However one can not exclude a possibility that at some relation between the dopant concentration and the degree of compensation the real Anderson transition can occur in the impurity band. Namely, the real quasimetallic conductivity can be achieved when the Fermi level reaches the mobility edge. Indeed, one of our samples demonstrated such a behavior - at the dopant concentration $5 \cdot 10^{11} \text{ cm}^{-2}$ and weak compensation the conductivity and magnetoresistance demonstrated weak localization behavior [5].

At the same time for strongly compensated sample 4 the activation energy ε_1 (obtained from the Hall measurements) is $\sim 40 \text{ meV}$ which significantly exceeds the corresponding energies for weakly compensated samples. Then, at low temperatures the temperature behavior of conductivity exhibits activation energy $\varepsilon_3 \sim 10 \text{ meV}$. If one attributes this energy to the nearest neighbor hopping, it also coincides with a halwidth of the impurity band.

$$N_A a^2 \geq \frac{\alpha}{\ln(\varepsilon_0/(\Delta\varepsilon_0))} \quad (10)$$

Thus an absence of the virtual Anderson transition as well as a significant increase of the energies ε_1 and ε_3 at strong compensation is explained by a strong increase of the bandwidth due to the Coulomb effects. In this case $\varepsilon_1 = \varepsilon_0 + \varepsilon_3$, which for $\varepsilon_0 = 30 \text{ meV}$ gives the observed energy $\varepsilon_1 = 40 \text{ meV}$.

2. Role of the dopant concentration.

It is of some paradox that an increase of the dopant concentration (for a given small degree of compensation) should initially lead to a suppression of the virtual Anderson transition. Indeed, the increase of concentration leads to a broadening of the impurity band due to overlapping of the wavefunctions of the neighboring sites which we denote as ε_T . If $\Delta\varepsilon_T > \Delta\varepsilon_0$ one expects an overlap of the tails of the two Hubbard bands. This fact leads to an appearance of the charged states within the impurity band and, correspondingly, of the related disorder potential. The latter can be estimated by a standard expression 7, however instead of the concentration of the charged centers one should insert the concentration of doubly occupied N_A^+ centers resulting from the overlap of the Hubbard bands. Thus, according to 8 it initially leads to a suppression of delocalization. However one has in mind that the overlap of the Hubbard bands exponentially depends on the dopant concentration while the overlap mentioned above finally leads to the Mott

transition and, correspondingly, to non-activated metallic conductivity. It is such a behavior which is observed for strongly doped sample 1. This sample demonstrates weak temperature behavior of conductivity and Hall effect while low-temperature MR demonstrates effects of weak localization and antilocalization (at weak magnetic fields), Fig.3.

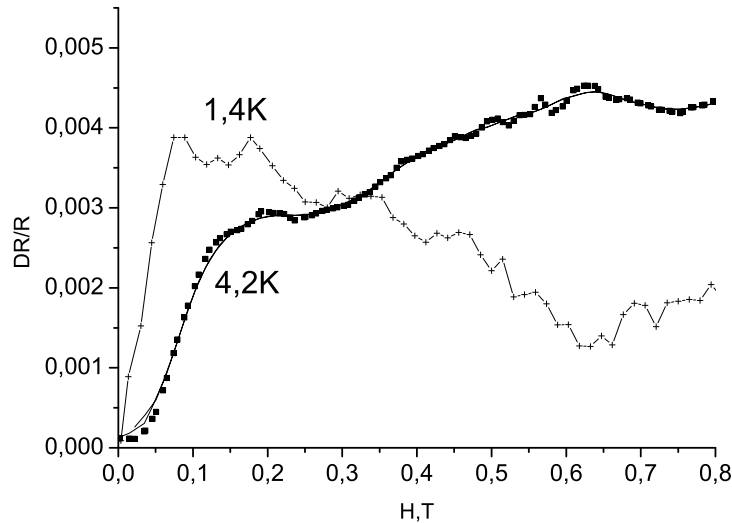


FIG. 3: Magnetoresistance curves for sample 1

This correlates with a behavior of dirty metals. As it was noted above, this behavior results from the Mott transition (that is from the strong overlap of the upper and lower Hubbard bands).

IV. CONCLUSION

Thus we have shown that an increase of the compensation degree in the samples, demonstrating virtual Anderson transition, initially leads to an increase of the low temperature conductivity. However a further increase of the degree of compensation leads to a suppression of the transition (and, correspondingly, to a decrease of the conductivity) due to an increase of the disorder potential. In its turn, an increase of the dopant concentration initially can also lead to a suppression of the Anderson transition, however at large dopant concentration the Mott transition takes place, and the sample becomes to be metallic. Since we predicted earlier such a behavior for the virtual Anderson transition [1], [2], the results reported in this paper give an additional support to our model.

V. ACKNOWLEDGEMENTS

The paper was supported by RFBR foundation (Project 10-02-00544).

-
- [1] Agrinskaya N.V., Kozub, V.I., Poloskin D.S. *Jetp Lett.*, **85**, 169 (2007)
 - [2] N. V. Agrinskaya, V. I. Kozub, Yu. M. Galperin, D. V. Shamshur *J. Phys.: Condens. Matter* **20**, 395216 (2008)
 - [3] Agrinskaya N.V., Kozub V.I., Poloskin D.S. *Semiconductors*, **44**, 472 (2010)
 - [4] A. L. Efros, B. I. Shklovskii, *Electronic properties of doped semiconductors* (Springer-Verlag, 1984).
 - [5] Agrinskaya N.V., Kozub V.I., Poloskin D.V., Chernyaev A.V., Shamshur D.V. *Jetp Lett.*, **80**, 30 (2004)